Lasers in Surgery and Medicine 20:242–247 (1997)

Fast and Effective Skin Ablation With an Er:YAG Laser: Determination of Ablation Rates and Thermal Damage Zones

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Background and Objective: **Er:YAG lasers are known to superficially ablate skin and other tissues with minimal thermal coagulation zones. The ablation efficacy and thus the clinical applicability of these lasers, however, was limited due to small beam diameters and repetition rates. Aim of this study was to determine the ablation efficacy and the amount of thermal damage with a new high-power high-repetition-rate Er:YAG laser and to find optimal treatment parameters for skin ablation.**
Study Design/Materials and Methods: **In vitro and some in vivo ablation trials on human skin were performed with the Er:YAG laser (MCL 29, Aesculap-Meditec, Heroldsberg, Germany, 2.94 µm, max. 500 mJ per pulse, 250 µs pulse length, 3 or 4 mm spot size, repetition rate 7–10 Hz) and evaluated microscopically.**
Results: **The ablation threshold was around 1.6 J/cm^2. The ablation rates increased linearly with the fluence, and the above-threshold ablation efficacy was around 2.5 µm per pulse per J/cm^2, leading to ablation velocities of 70–100 µm per second and higher. With increasing pulse numbers applied to one tissue spot, the ablation per pulse decreased significantly. The amount of thermal damage was clearly dependent on the number of pulses applied (around 25 µm with <10 imp., up to 100 µm with 40 imp.), whereas higher fluences increased the coagulation zones only minimally. The in vivo trials confirmed these results: overlapping pulses in the 4 J/cm^2-range, applied in a sweeping motion, proved optimal for an efficient skin ablation with a smooth resulting surface and a thermal damage zone not exceeding 50 µm.**
Conclusions: **The high power and the high repetition frequency make this laser a fast and effective tool for skin ablation without increasing the thermal damage, but the ablation remains limited to the superficial dermis, since hemostasis cannot be achieved due to the absence of coagulation. Lasers Surg. Medicine 20:242–247, 1997.**

Key words: 2.94µm wavelength; laser dermabrasion; thermal coagulation; hemostasis

INTRODUCTION

Due to the high absorption of the 2.94 µm-wavelength in water and in water-containing tissues like skin, the radiation of an Er:YAG (*Er*bium-doted *Y*ttrium-*A*luminium-*G*arnet) laser is almost totally absorbed in a very thin, superficial tissue layer [1,2]. Thus, the irradiant energy of the laser pulse is contained in a relatively small tissue volume, which should theoretically lead to an effective superficial skin ablation. Because of the small penetration depth (absorption coefficient 12960 cm^{-1}, theoretical penetration depth about 1 µm [2]) and the short pulse length of an Er:YAG laser in free-running mode ("macropulse" of about 250 µs, consisting of a train of 1 µs-long micropulses), the heat conduction into the

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Accepted for publication 13 May 1996.

surrounding tissue should be minimal, resulting in a minimal remaining coagulation damage. Indeed, thermal necrosis zones not exceeding 30–50 μm have been confirmed by many authors both in vitro and in vivo [1,3–6].

The absence of tissue coagulation, however, restricts the achievable ablation depth due to bleeding that occurs when the vessels of the superficial dermal plexus are severed [3,4,6]. Therefore, the ablation potential of the typical Er:YAG laser, in contrast to the classical mechanical dermabrasion, is limited and comparable to a superficial dermabrasion or a medium-depth chemical peel. But even for these superficial lesions, the lasers available so far have been not very well suited for clinical application due to very slow ablation velocities (small beam diameters, low energy output and repetition frequencies [4]).

With a new high-power Er:YAG laser (model MCL 29, Aesculap-Meditec, Heroldsberg, Germany), spot sizes of 3 and 4 mm diameter are possible due to a maximum pulse energy of 500 mJ with a repetition frequency of 7–10 Hz. The aims of this study were: i) to determine the ablation rates achievable with this laser system, and ii) to examine whether high fluences and/or repetition rates would increase the zone of thermal necrosis. Therefore, we conducted in vitro measurements on human skin with varying diameters, fluences, and pulse numbers together with some in vivo trials in order to establish the optimal irradiation parameters for a fast and effective skin ablation.

MATERIALS AND METHODS

For these investigations, we used a prototype of the Er:YAG-laser MCL 29 (Aesculap-Meditec) that is commercially available. It is fitted with an optical fiber transmission system and a 532 nm-low-level krypton laser aiming beam. The output energy can be selected between 100 and 500 mJ in 50-mJ steps, the pulse length is about 250 μs (macropulse, consisting of a train of 1-μs-micropulses), and the repetition frequency can be varied between 7 and 10 Hz. By interchangeable handpieces with integrated distance holders, the laser beam can be focused to spot sizes on the skin of 3 and 4 mm, respectively.

The spot sizes were confirmed by measuring the diameter of 100-mJ-laser shots on burn paper. The beam profile in the treatment spot (after optical fiber and handpiece) was measured with 350 mJ-pulses and the 3 mm handpiece using the beam attenuation method with glass (Ophir model AP 11, Haifa, Israel) slides and a power meter. Figure 1 shows that the beam profile is nearly hat-shaped with steep flanks resembling the beam profile described by Walsh and Deutsch [7]. The effective beam diameter as the central part of the beam where the fluence is above $1/e^2$ (≈14%) of the maximum fluence, is closely in the range of the 3 mm-spot size measured on burn paper. This concurs with the results of Kaufmann and Hibst [6].

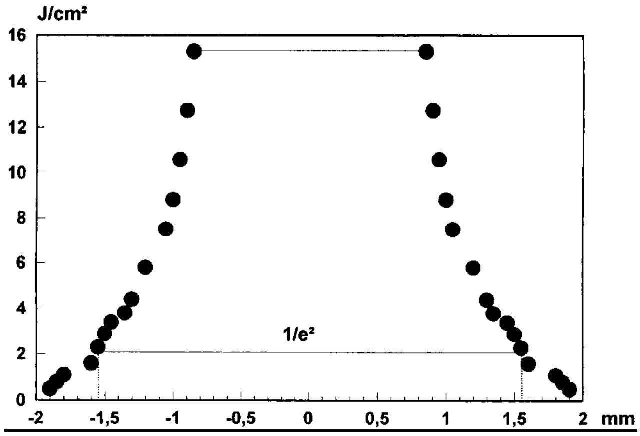

Fig. 1. Beam profile on the skin (350 mJ, 3 mm spot size). Lower line marks the effective beam diameter ($1/e^2$-range, see text).

For this study, we determined to use the average fluences calculated from the energy per pulse and the beam diameter (Table 1). Although the *real* fluences measured in the beam center are higher (Fig. 1), the *average* fluences are used in most Er:YAG laser studies [1,3–7] and thus are important for the comparability of the results.

For the in vitro experiments, freshly excised healthy human skin (from the safety margins of melanoma or other malignant skin tumor excisions) was stored in wet dressings of 0.9% NaCl solution not longer than 2 hours before laser treatment. The tissue was then fixed on a horizontal plate and irradiated with the Er:YAG laser with the correct tissue-handpiece distance.

The resulting round tissue craters were then excised and fixed in 4%-formaldehyde solution. The paraffin-embedded tissue specimens were then cut to 8 μm-sections with special care to cut perpendicular to the surface and in the central area of the laser craters. The sections were stained with the hematoxylin-eosin (H&E) routine procedure.

The ablation depth and, for the later samples, the zone of thermal necrosis (eosinophilic ho-

TABLE 1. Er:YAG Laser Fluences (J/cm²) for the Different Output Energies and Spot Sizes

Output energy (mJ)	3 mm	4 mm
200	2.8	1.6
250	3.5	2
300	4.2	2.4
350	4.9	2.8
400	5.6	3.2
450	6.3	3.6
500	7	4

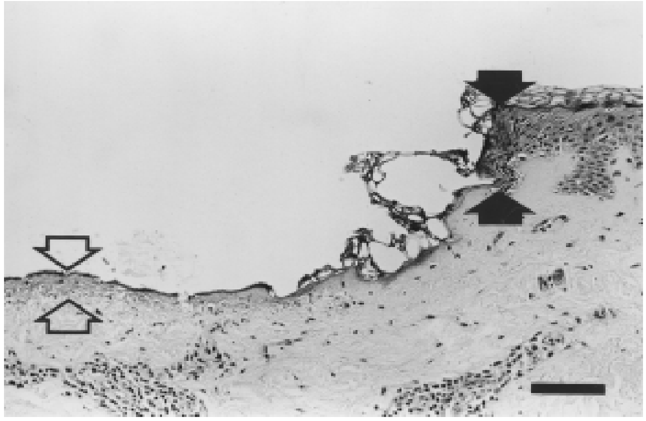

Fig. 2. Er:YAG ablation crater (500 mJ, 4 mm, 25 Imp.). The coagulation zone at the crater bottom (around 40 μm, open arrows) is smaller than at the edge (solid arrows). H&E, scale bar = 100 μm.

mogenization of collagen fibers, pycnosis of cell nuclei) were then evaluated light-microscopically for multiple sections of each tissue sample, and the respective maximum values were used for the computation of the results. For the generation of charts and the correlation coefficients (Pearson, two-tailed), the SPSS™ statistical program was used.

At first, only the 4-mm handpiece was available. For the evaluation of the ablation efficacy, series of 10, 20, 30, and 40 pulses were applied to one spot with pulse energies increased from 200 to 500 mJ in 50-mJ-steps.

As expected, with a 4 mm spot size and 500 mJ per pulse, the ablation was most effective. Therefore, these parameters were examined more intensively, as they were judged as most interesting for clinical applications. In 24 tissue samples treated with these parameters, ablation rates and thermal necrosis were examined for increasing pulse numbers (5 to 40).

When the 3mm-handpiece became available, additional samples were irradiated with this spot size (10, 20, 30, and 40 pulses with 200 to 500 mJ in 100-mJ-steps) and evaluated for ablation and necrosis. The repetition rate was 7 Hz in all cases.

To test the clinical applicability of this laser, in vivo ablation trials were conducted in three consenting patients in the safety margins of melanomas while the patient was under general anesthesia for tumor excision. Any additional local application of epinephrine, e.g., for hemostasis, was avoided. Small areas of skin (Fig. 7) were irradiated with both handpieces and varying output energy to find an optimal application technique and to examine the bleeding tendency with deeper ablation. Histologic specimens were taken after the excision of the tissue block to examine the thermal necrosis.

RESULTS

Sixty-eight different tissue samples have been irradiated for this study. Unfortunately, even with utmost regard for correct histological technique, only 60 specimens were evaluable due to oblique cutting or other procedural mistakes.

Clinically, the ablation threshold was found to be around 1.6 J/cm², which corresponds to a 200-mJ-pulse with 4 mm spot size. With lower energy densities, no ablation could be detected. With all fluences and pulse numbers, light-microscopically the ablation craters showed a flat and even bottom with a homogenous zone of thermal damage. The edges of the surrounding tissue were smooth with low pulse numbers and more steep with high pulse numbers and generally showed an increased thermal damage zone compared to the crater bottom (Fig. 2). With increasing pulse numbers and fluences, the coagulation zone in the crater bottom got more pronounced, and so did the thermal damage of the crater edges (broad epidermal coagulation, sometimes with subepidermal blistering).

Ablation Rates

In each of the 60 samples, the ablation rates were measured. Figure 3 shows the ablation per pulse according to the energy density for all samples. The ablation per pulse increases nearly linearly with increasing fluence (correlation coefficient (CC) 0.82, $P < 0.001$). The average ablation per pulse for every Joule/cm² above the ablation threshold is around 2.5 μm, leading to a theoret-

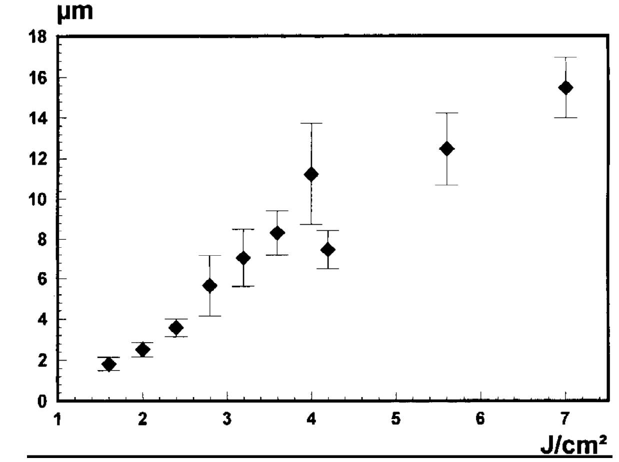

Fig. 3. Ablation per pulse (µm) vs. fluence (J/cm^2). Mean values with error bars giving the standard error of the mean (SEM). All fluences, n = 60.

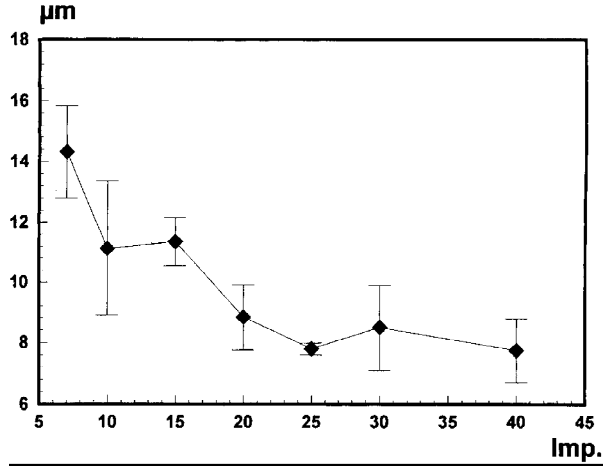

Fig. 4. Ablation per pulse (µm) vs. number of pulses. Mean values with error bars giving the SEM. Fluence range 3.6 –4.2 J/cm^2, n = 32.

ical vertical ablation velocity of ca. 70 µm per second with 4 J/cm^2 and 7 Hz repetition rate.

Figure 4 shows the influence of the number of pulses applied upon the ablation efficacy per pulse. For the treatment technique, it is important to know whether applying multiple pulses to one tissue spot will decrease the ablation efficacy. To investigate this, we chose the 32 samples of the 4 J/cm^2-fluence range (3.6–4.2 J/cm^2) since these fluences proved optimal for treatment (see in vivo results).

With increasing pulse numbers to one spot of tissue, the ablation per pulse decreases significantly (CC 0.70, $P < 0.001$). For example, with the 500 mJ/4 mm parameter combination and pulse numbers up to 10, the average ablation is 13.6 ± 2.29 µm per pulse (11 cases), whereas with 30 pulses and more, it drops to 8.9 ± 1.26 µm (4 cases).

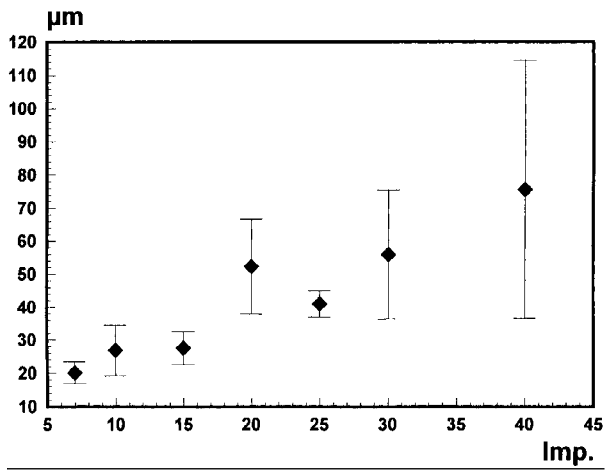

Fig. 5. Depth of coagulation zone (µm) vs. number of pulses. Mean values with error bars giving the SEM. All fluences, n = 38.

Thermal Necrosis

The zone of thermal necrosis was determined in 38 samples. The degree of thermal necrosis is clearly dependent on the number of pulses applied, as Fig. 5 shows (CC 0.69, $P < 0.001$). In contrast, the laser fluence is of much less importance for the depth of necrosis (Fig. 6, CC 0.37, $P = 0.02$). In this figure, the depth of necrosis *per pulse* is shown in relation to the fluence to eliminate, at least partially, the influence of the pulse numbers.

As figure 5 shows, the average thermal necrosis with small pulse numbers (up to 10) is only between 20 and 50 µm for all fluences investigated.

In Vivo Application

As mentioned above, ablation trials were carried out in vivo in safety margins of skin tumors to find the optimal treatment technique. By moving the handpiece slowly over the area to be treated and using a repetition frequency of 7 Hz, the resulting overlapping pulses created a smooth and even epidermal ablation. Fluences in the 4 J/cm^2-range (450–500 mJ with 4 mm, 300–350 mJ with 3 mm spot size) proved to be optimal for a smooth and simultaneously effective ablation. With lower fluences, ablation velocities were too

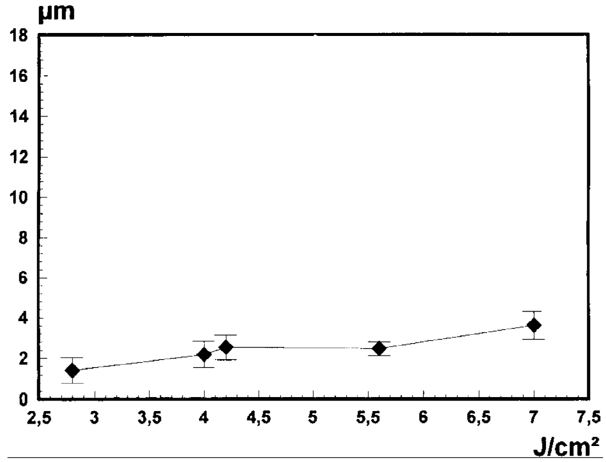

Fig. 6. Depth of coagulation zone *per pulse* vs. fluence (n = 38). Mean values with error bars giving the SEM.

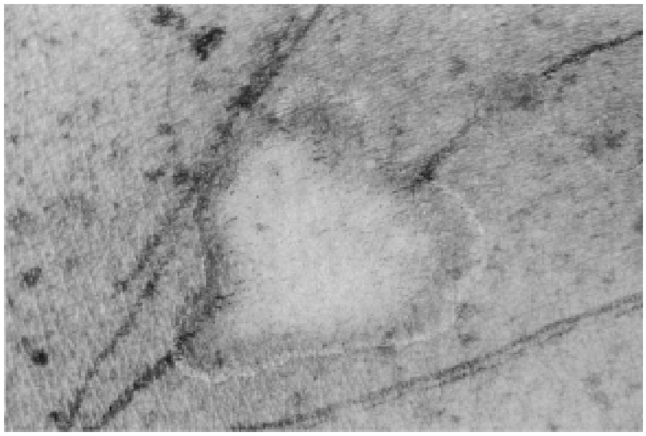

Fig. 7. Smooth, clear, debris-free ablation in vivo (500 mJ, 4 mm) with blending into the surrounding skin.

low and debris formation increased, whereas with higher fluences, the ablated surface tended to be irregular due to high ablation depths per single pulse.

With the optimal parameters, the minimal, grayish debris on the surface can be easily removed with wet gauze, and by "feathering" out the edges with single pulses, the ablation area can be smoothly blended into the surrounding skin (Fig. 7). Several passes over the same area resulted in deeper ablation of the dermis and, consecutively, to pinpoint bleeding. Continuing the irradiation lead to more pronounced hemorrhage that prevented any further ablation.

Histologically, the remaining coagulation zone did not exceed 50 μm (three samples, H&E-staining).

DISCUSSION

Our results regarding the ablation threshold and the ablation efficacy of the Er:YAG laser concur well with the results reported in literature. In our study, the ablation threshold was around 1.6 J/cm^2, compared to 1.5 and 1.7 J/cm^2 as reported by Kaufmann and Hibst [3] and Walsh and Deutsch [7]. Our ablation efficacy of about 2 μm of tissue per pulse per J/cm^2 is well in the range of all results reported with similar repetition rates of at least 2 Hz and energy densities up to 10 J/cm^2 (around 2 μm per pulse per J/cm^2 in [6–8]).

These clinically measured ablation rates per pulse of up to 16 μm (our work), 30 μm [1] and even 400 μm [7] seem to be contradictory to the Er:YAG laser penetration depth in water of around 1 μm [2]. Walsh and Cummings explained this contradiction by assuming a change in the optical properties of water (very much lower absorbance) with high-irradiance laser pulses that would be consistent with the published ablation efficacies [2].

Regarding the coagulation zones, our findings also concur well with other results. Many authors have shown in vitro and in vivo that with the Er:YAG laser, thermal necrosis zones do not exceed 30–50 μm [1,3–6,8].

Most of these experiments, however, were carried out with repetition rates of 1 or 2 Hz [1,3,5,8], and with these frequencies, most authors could not find an increase of the thermal necrosis with the number of pulses applied [3,8]. Using 5 Hz, Kaufmann and Hibst [4] found that the crater-adjacent necrosis increased with the energy and the pulse number, whereas at the crater bottom, the necrosis was constantly around 50 μm.

In our results using 7 Hz and large beam diameters, we could confirm histologically that the crater-adjacent necrosis increased with the pulse number and the fluence, although this was not quantified. Additionally, however, we found the zone of necrosis to clearly increase with the number of pulses applied to one spot, and the ablation efficacy decreased significantly with increasing pulse numbers. Both observations could be explained by a cumulation of the thermal side effects due to the repeated laser pulses. The relatively high repetition frequency leads to a successive temperature rise in the skin, enhanced by the in vitro situation where the cooling by circulation

is absent. Thus, on one hand the coagulation zone increases and, on the other hand, due to exsiccation of the tissue by water loss, the H_2O-dependent tissue absorbance of the Er:YAG laser radiation is reduced leading to a decreased ablation efficacy.

A similar effect was also reported by Kaufmann and Hibst [6]. With 14 J/cm^2 and 1 Hz repetition rate, they found a decrease of the ablation rate from 30 μm to 22 μm when increasing the pulse numbers from 20 to 120. In the same article, they predicted an increase of the remaining coagulation zone with higher repetition frequencies [6].

In the clinical setting, however, where the beam is moved over the ablation area and one tissue spot is irradiated with only some single pulses at one time, these effects are avoided and the resulting tissue necrosis even with high fluences will not exceed 50 μm, as our in vitro results show (Fig. 5). This was confirmed by the in vivo measurements, where the damage zone measured no more than 50 μm in all three cases investigated. Therefore, a fast and uncomplicated healing process can be supposed for the Er:YAG laser ablation of skin, as first clinical and animal-experimental results seem to confirm [3,4,6].

Although these minimal remaining thermal coagulation zones are important for wound healing, they cannot achieve intraoperative hemostasis as in the larger coagulation zones of the carbon dioxide laser. As our in vivo trials confirmed, the ablation depth remains limited to the superficial dermis, since bleeding from the superficial dermal vessel plexus not only obscures the operating field, but effectively prevents further ablation due to the total absorption of the laser light in the thin layer of blood [3,4]. Therefore, the clinical indications of the Er:YAG laser are limited and comparable to those of a rather superficial dermabrasion or a medium-depth chemical peel, in our opinion as well as in the opinion of other authors [3,4].

Up to now, the clinical applicability of the Er:YAG lasers was further limited due to the available irradiation parameters. Small beam diameters (max. 1.1 mm, [1,3,5,6,8,9]), low repetition frequency (1–2 Hz [1,3,5,6,8,9]) and, with some lasers, limited energy output (max. 250 mJ in [1,4]), made the clinical ablation process "a time-consuming procedure for both the physician and the patient" [4].

Typical ablation rates for an 1.1 mm spot are about 2–3 μm per pulse per Joule/cm^2 of incident fluence [3,6,7], leading to average ablation rates of 8–21 μm per second of treatment (given the typical energy range of 4–7 J/cm^2 and a repetition frequency of 1 Hz). Accordingly, the ablation of a skin lesion that is only 100 μm thick and measures 3 cm in diameter, would require 60 to 150 minutes with these parameters. Higher incident fluences up to 80 J/cm^2 with resulting ablation rates of max. 400 μm per pulse are restricted to small beam diameters [8,9] and are not suited for clinical ablation of skin as they result in very irregular surfaces ("drilling" effect).

In contrast, the large spot sizes of 3 and 4 mm allow a smooth, dermabrasion-like ablation, and the high repetition rates and energy output make it fast and effective. For example, the above mentioned theoretical skin lesion could be ablated in less than 2 minutes with the 4 mm–500mJ parameter combination (see Results).

In summary, our results confirm the fact that large spot sizes and high repetition frequencies do not lead to increased thermal coagulation and furthermore show that the Er:YAG-laser can be an effective tool for superficial skin ablation, despite its limitation to the level of the superficial dermis.

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